



# A Distributed Time-Difference of Arrival Algorithm for Acoustic Bearing Estimation

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# Outline

⇒ • **Motivation**

- **Time-Difference of Arrival Algorithm**
- **Time synchronization**
- **GPS averaging**
- **Reference coherent bearing estimates**
- **Summary**



# Motivation

- Algorithm that produces instantaneous position estimates
- Tracker that operates outside the field of sensors
- Algorithm that is invariant to analog gain
- Algorithm that assumes no target dynamics and does not constrain target motion
- Tracker whose accuracy scales with additional sensors



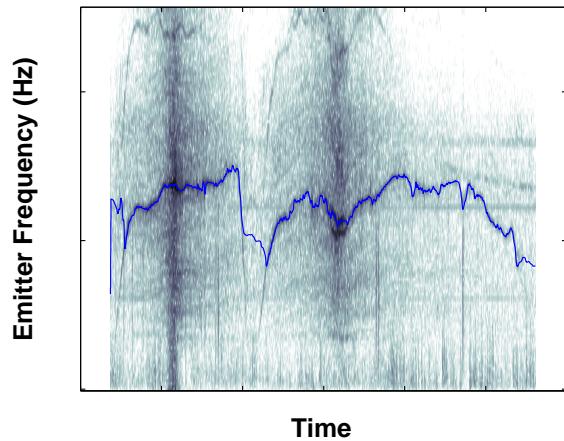
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- Motivation
- ⇒ ● Time-Difference of Arrival Algorithm
  - TDOA Estimation
  - Localization algorithms
  - TDOA Performance Simulations
  - TDOA Results from SITEX02
- Time synchronization
- GPS averaging
- Reference coherent bearing estimates
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# Acoustic Time-Difference of Arrival

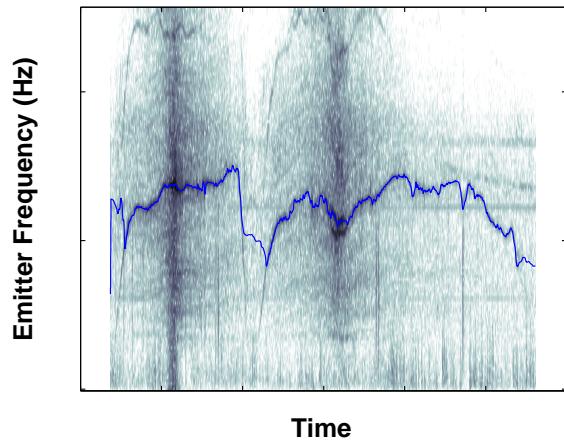
- Estimate dominant frequency on each node





# Acoustic Time-Difference of Arrival

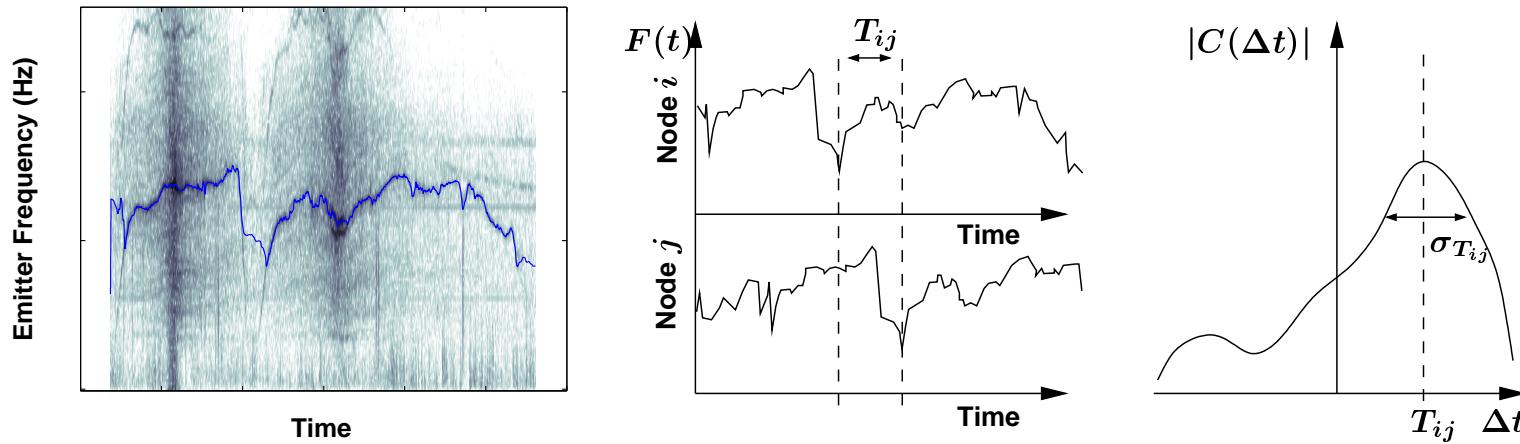
- Estimate dominant frequency on each node
- Downsample dominant frequency series, share among nodes





# Acoustic Time-Difference of Arrival

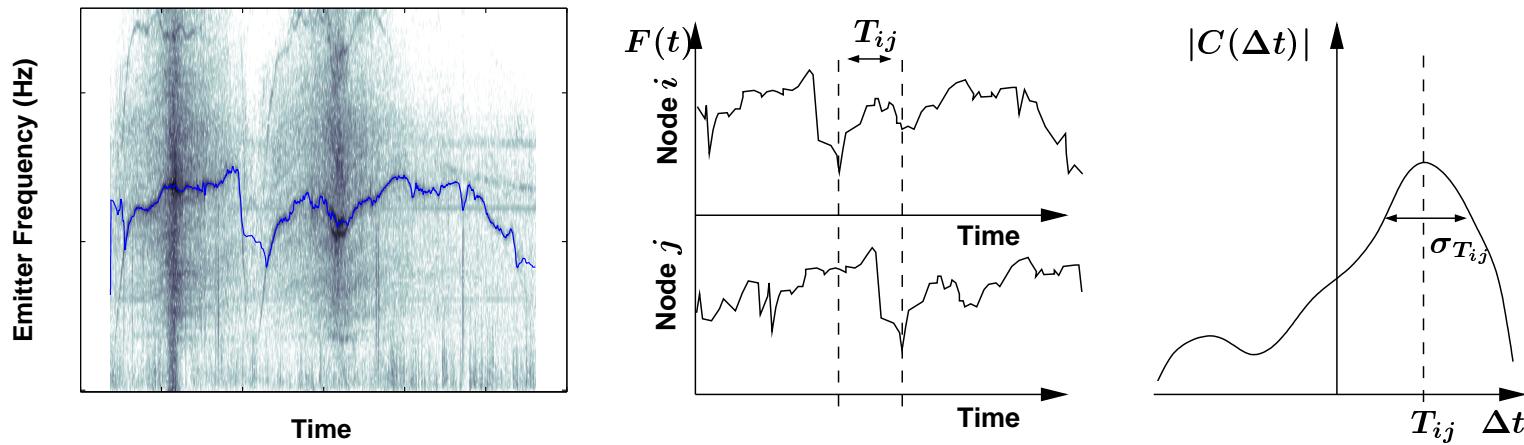
- Estimate dominant frequency on each node
- Downsample dominant frequency series, share among nodes
- Cross-correlate to determine time delays





# Acoustic Time-Difference of Arrival

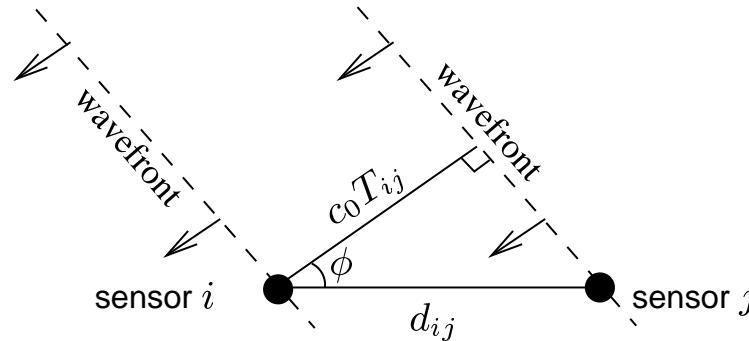
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# Bearing solution

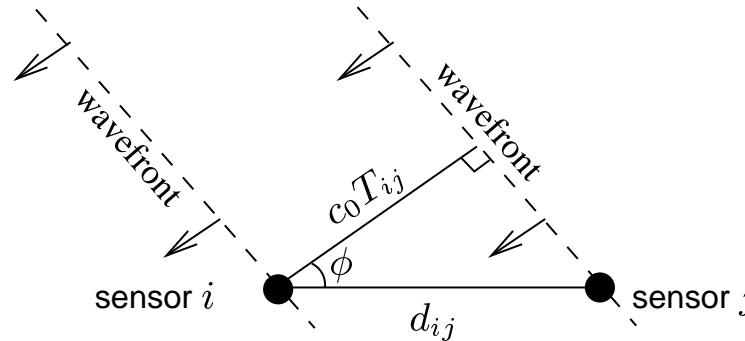
- Pairwise TDOA exchange gives two ambiguous bearings



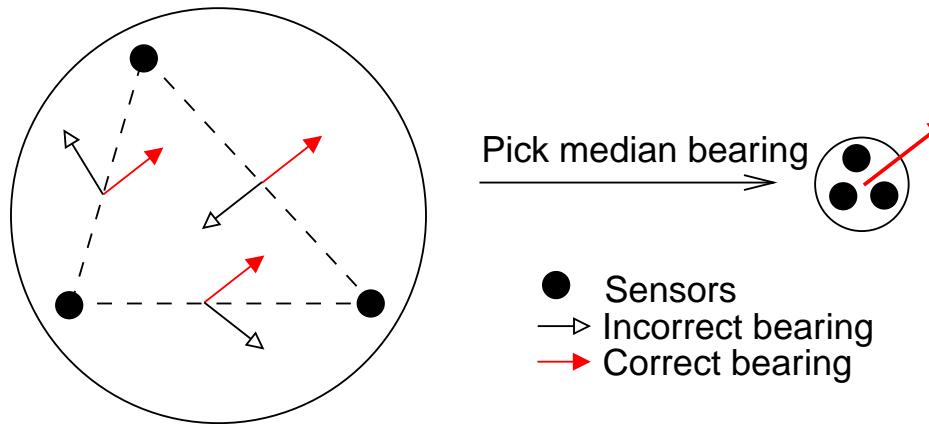


# Bearing solution

- Pairwise TDOA exchange gives two ambiguous bearings



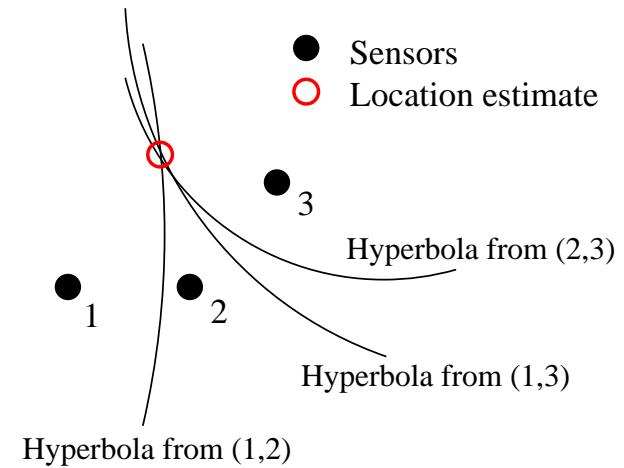
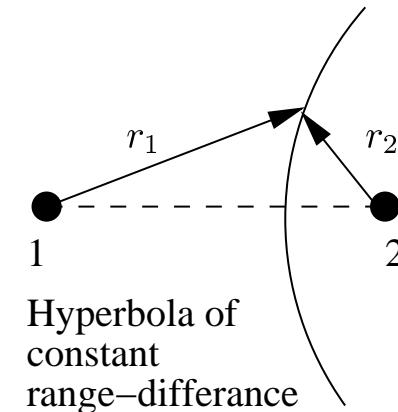
- With several sensor pairs, the correct estimate appears consistently, pick average bearing





# Hyperbolic location theory

- The hyperbola is the set of points at a constant *range-difference* ( $c_0 \Delta t$ ) from two foci
- Each sensor pair gives a hyperbola on which the emitter lies
- Location estimation is intersection of all hyperbolas

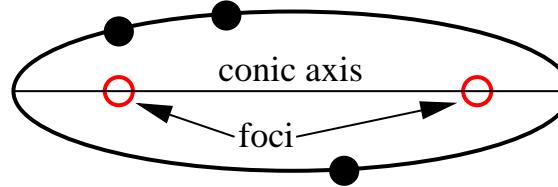




# Location on Conic Axis (LOCA) solution

- With three sensors, rewrite hyperbolic equations to form mathematical *dual*.
- Sensors on a conic with emitter at a focus.

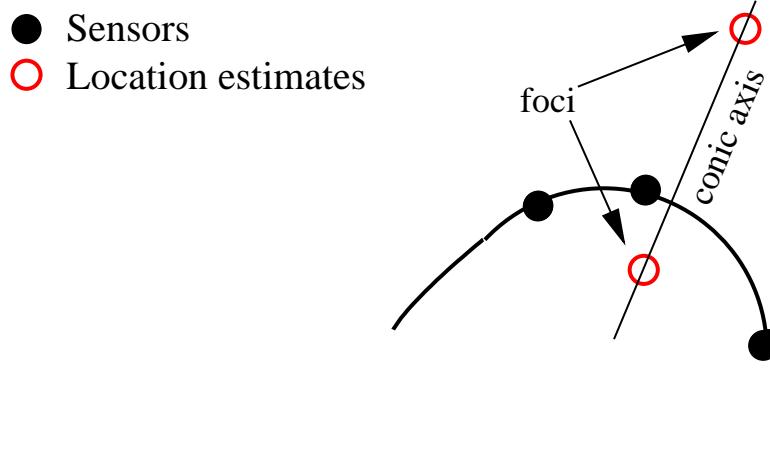
- Sensors
- Location estimates





# Location on Conic Axis (LOCA) solution

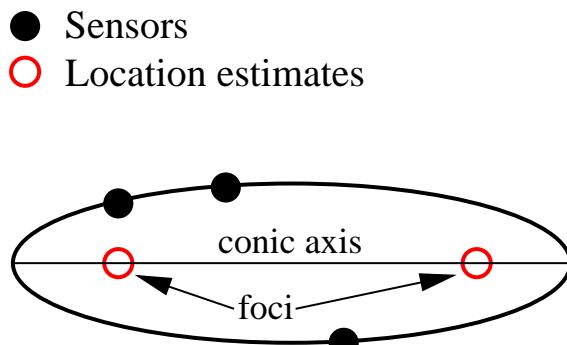
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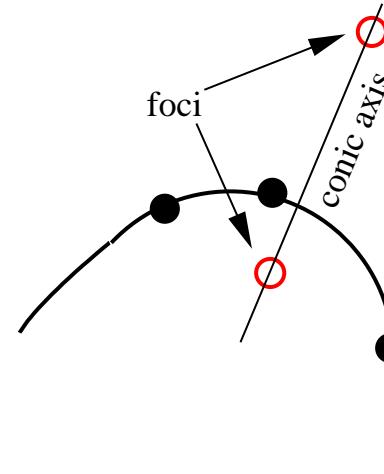


# Location on Conic Axis (LOCA) solution

- With three sensors, rewrite hyperbolic equations to form mathematical *dual*.
- Sensors on a conic with emitter at a focus.
- Foci ambiguity:
  - Conic is ellipse: the ‘wrong’ focus gives negative time-delays.
  - Conic is hyperbola: the ambiguity is unresolvable



Ellipse – removable ambiguity

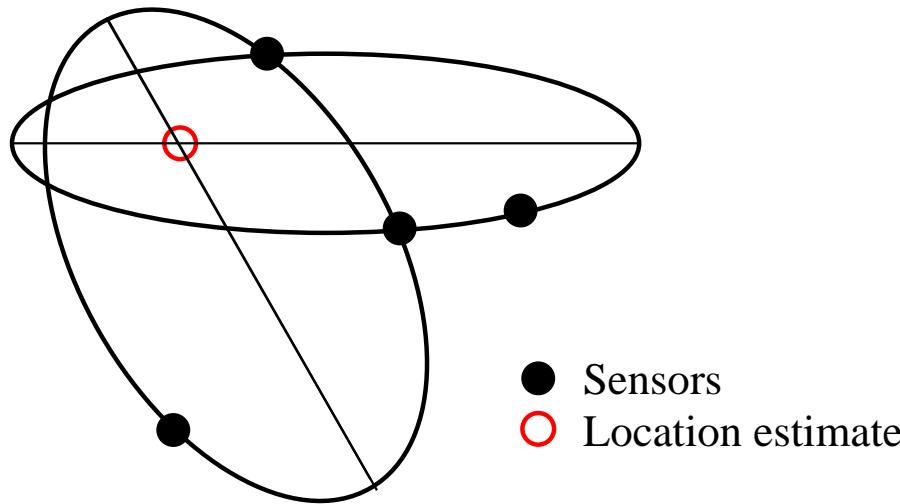


Hyperbola – unremovable ambiguity



# LOCA solution

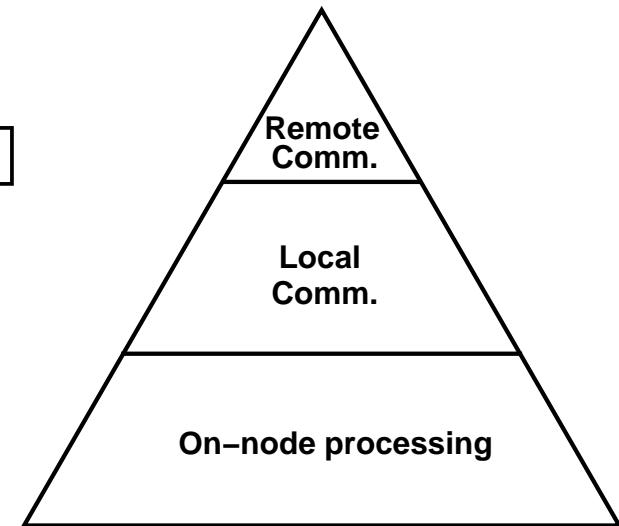
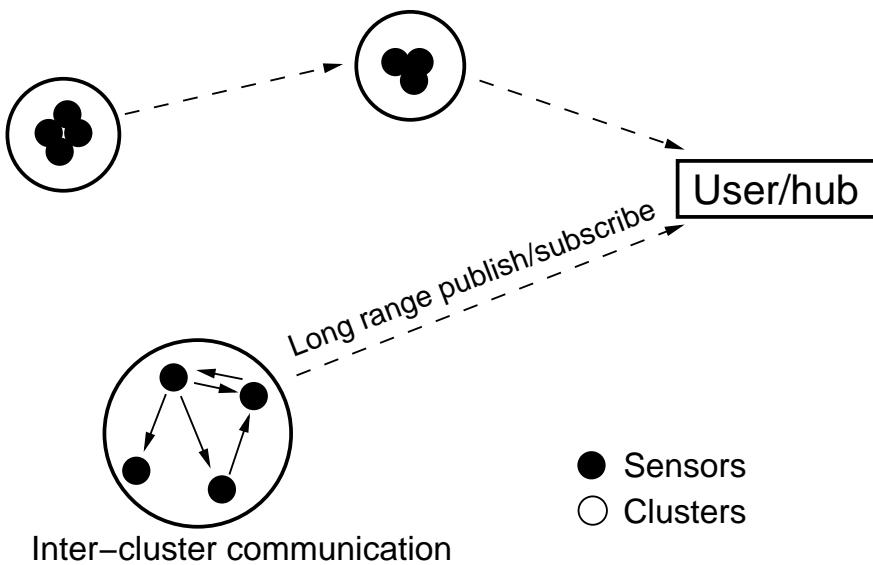
- With four or more sensors, conic type irrelevant
- Each triad of sensors gives a line (conic axis) containing emitter
  - Number of conic axes = Number of triads =  $\binom{N}{3} \sim O(N^3)$
- Least-squares solution finds the point closest to all the lines
- Feasible range-difference bivector correction as prefilter





# Clustered networks

- Intra-cluster distance is much less than inter-cluster distance.
- Compute TDOAs within clusters to minimize communication range
- Each cluster publishes results
- Users and other clusters subscribe with long distance communication and fuse results



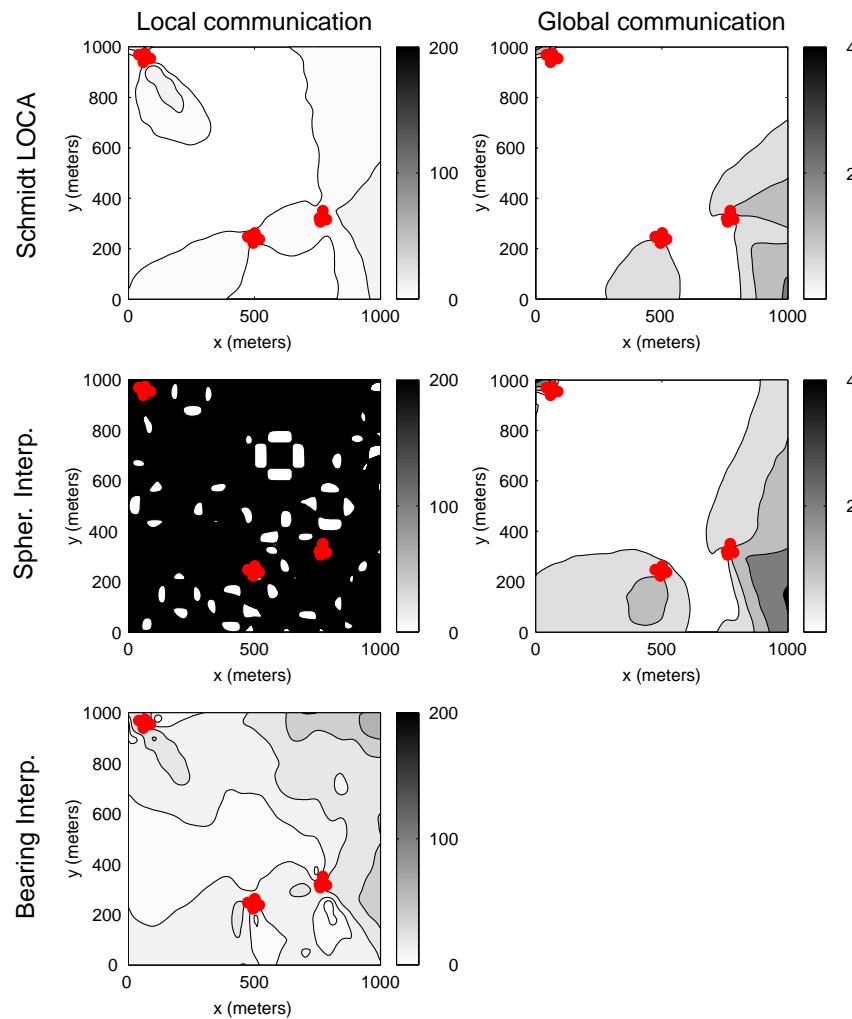


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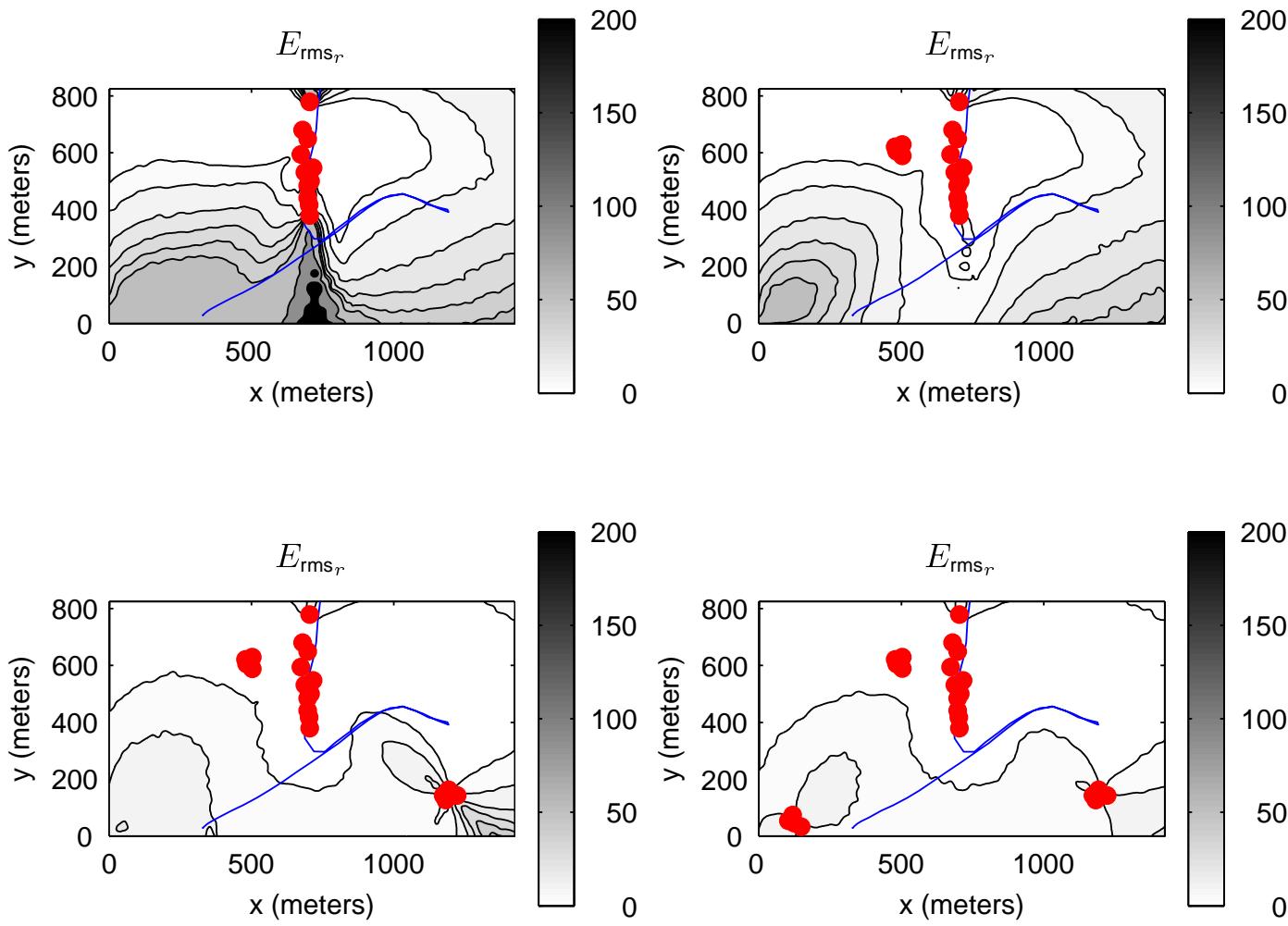


# Cluster communication constraints





# Geometric precision simulations



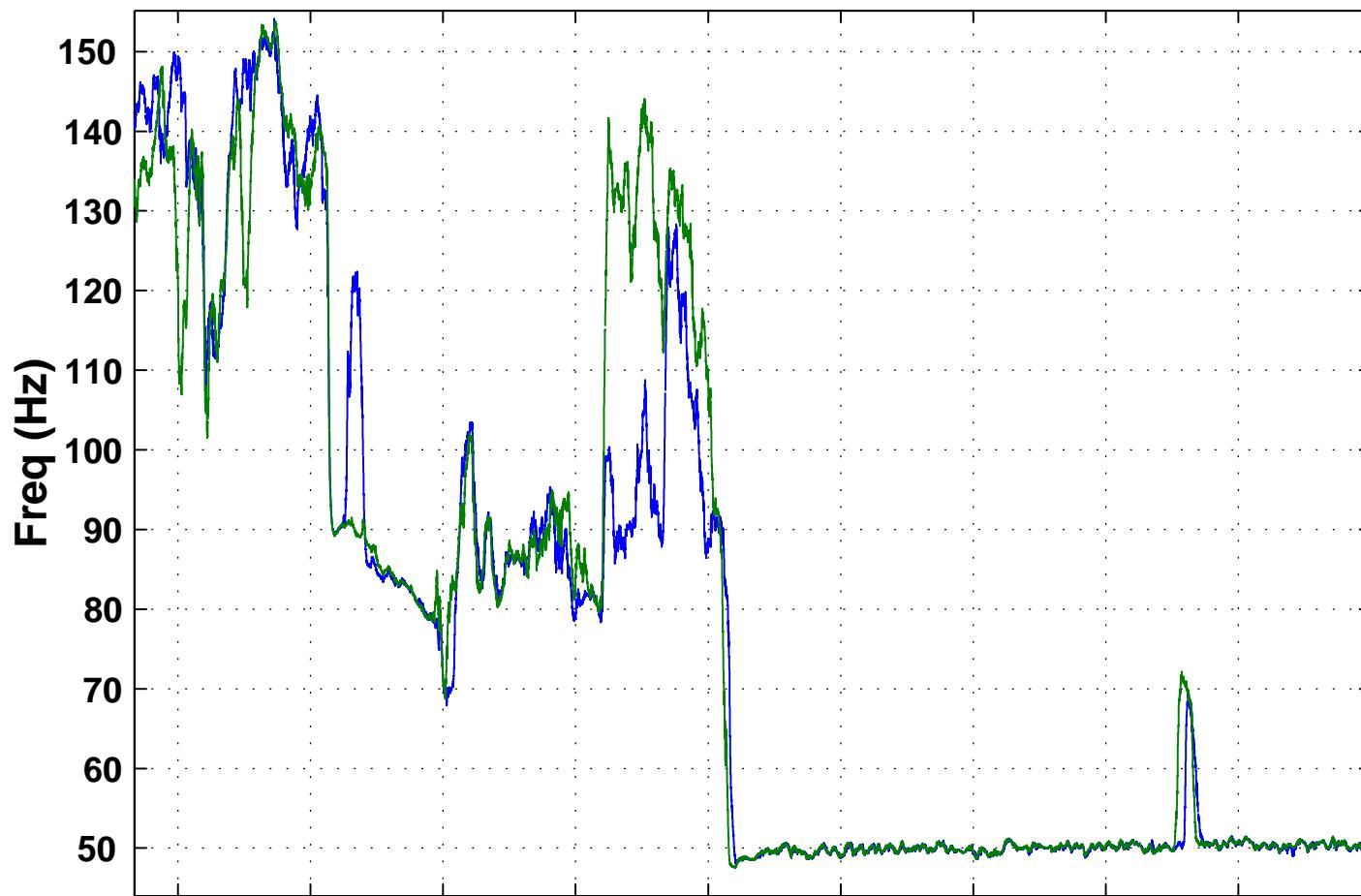


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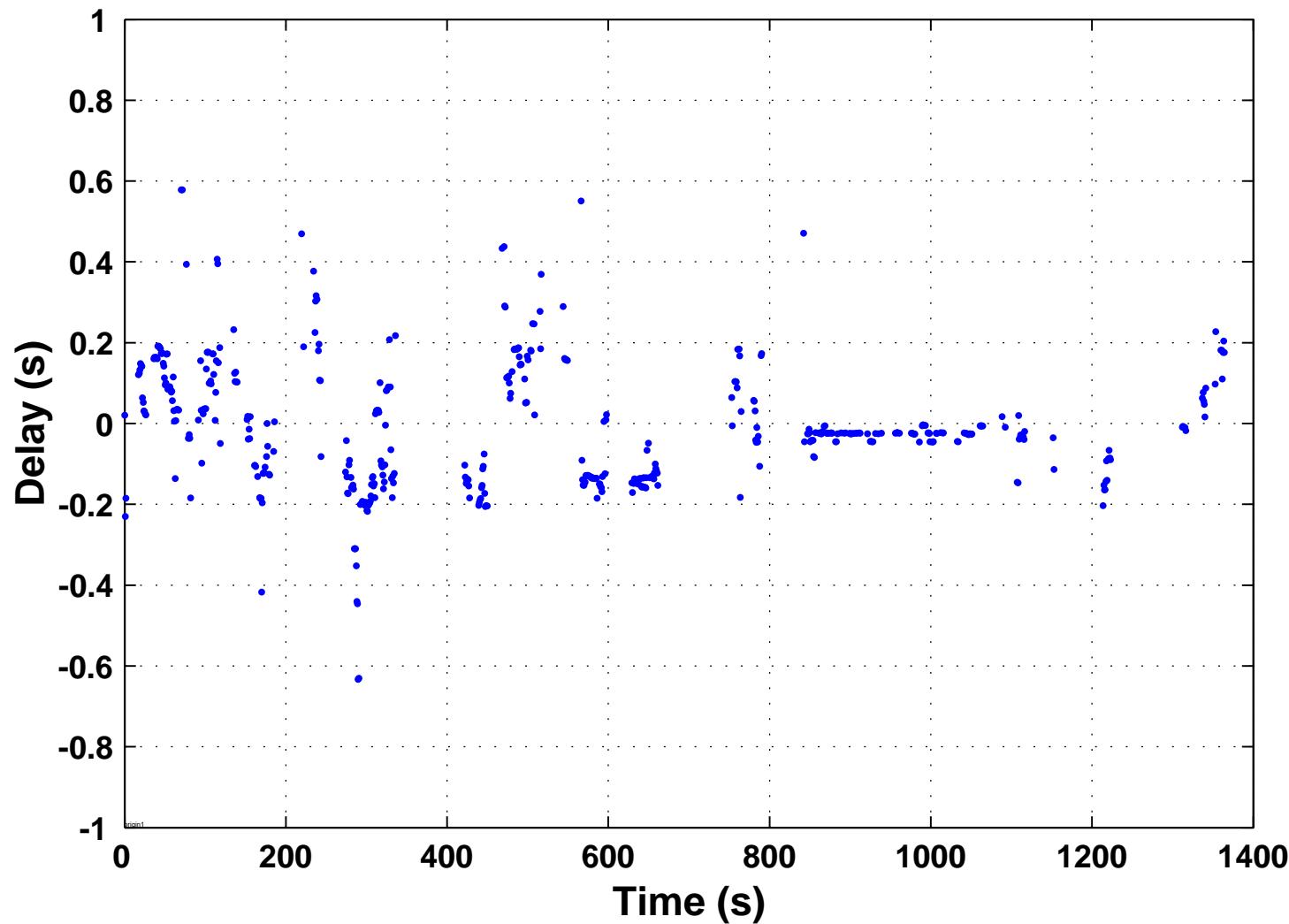


# SITEX02 Frequency Estimation





# SITEX02 2-Node Delay Estimation





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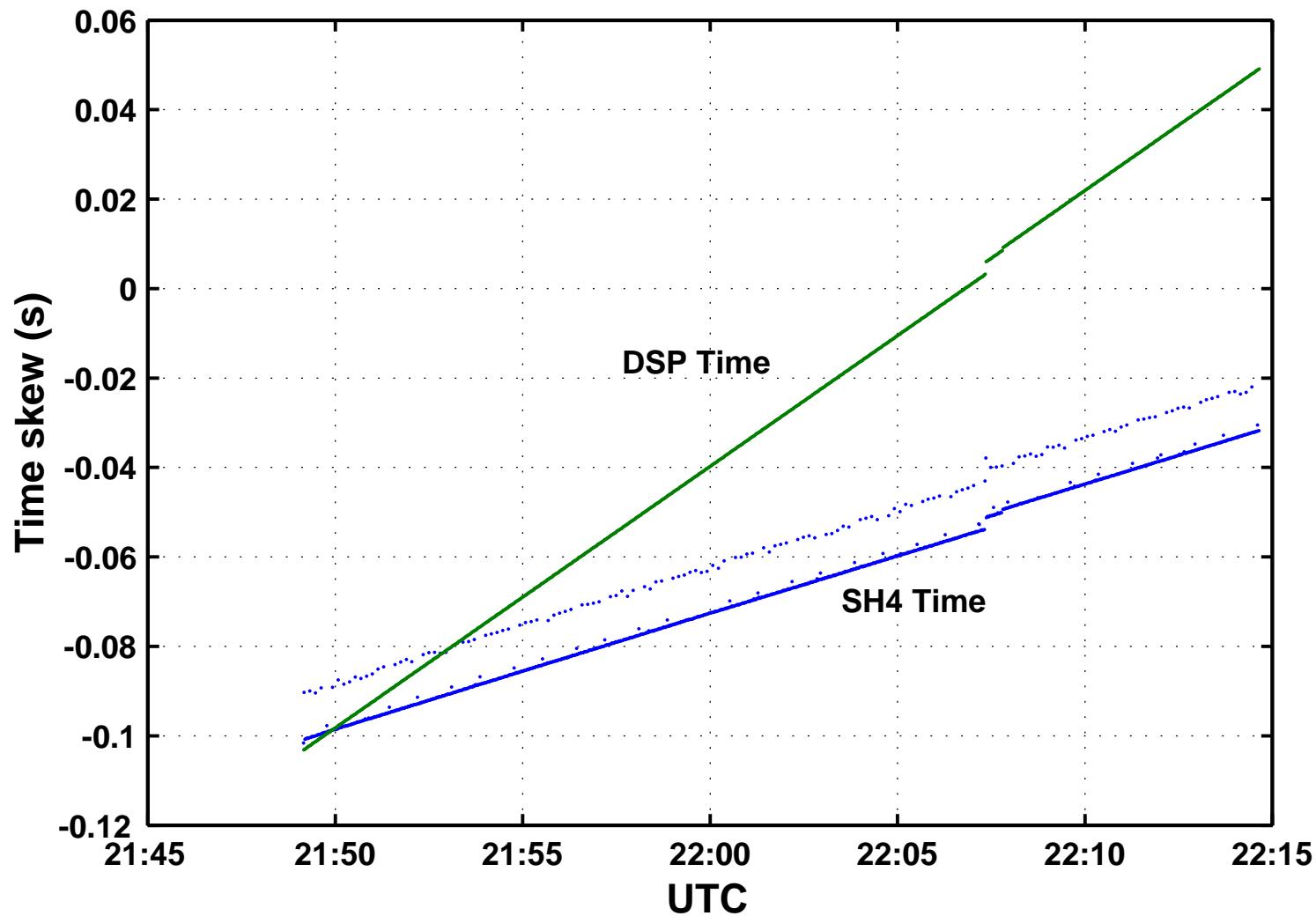


# Time synchronization

- Inter-node time synchronization is essential for many algorithms
  - Localization error is related to percentage error in time delay estimates.
  - Using nodes spaced at 100m, 2.9ms is 1% error
  - Nodes might be spaced more closely
- Crystal oscillators drift at 10-100 ppm, equivalent to accumulated error of 36-360 ms per hour of operation.
- External time reference is necessary.
- NTP is a free program for synchronizing computers over a network
- Also synchronizes clocks from reference signals (GPS, radio signal, etc)
  - GPS provides a timing signal accurate to 100ns.
  - Not available on Sensoria hardware (firmware/software upgrades will correct this)
- NTP network synchronization used for SITEX02. Accuracy often better than 10ms, depending on network load.

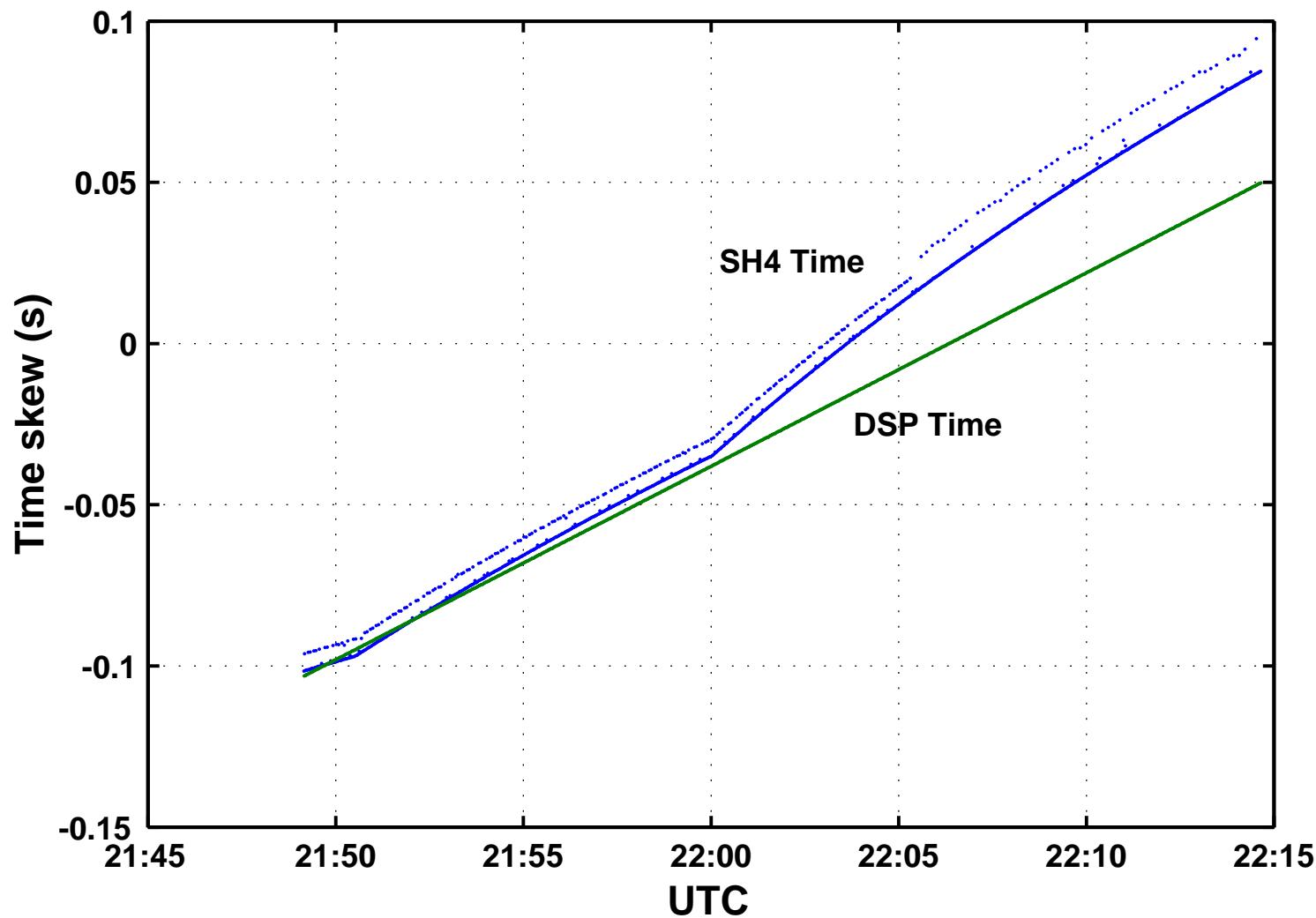


# Single Node Time Skew





# Time Skew





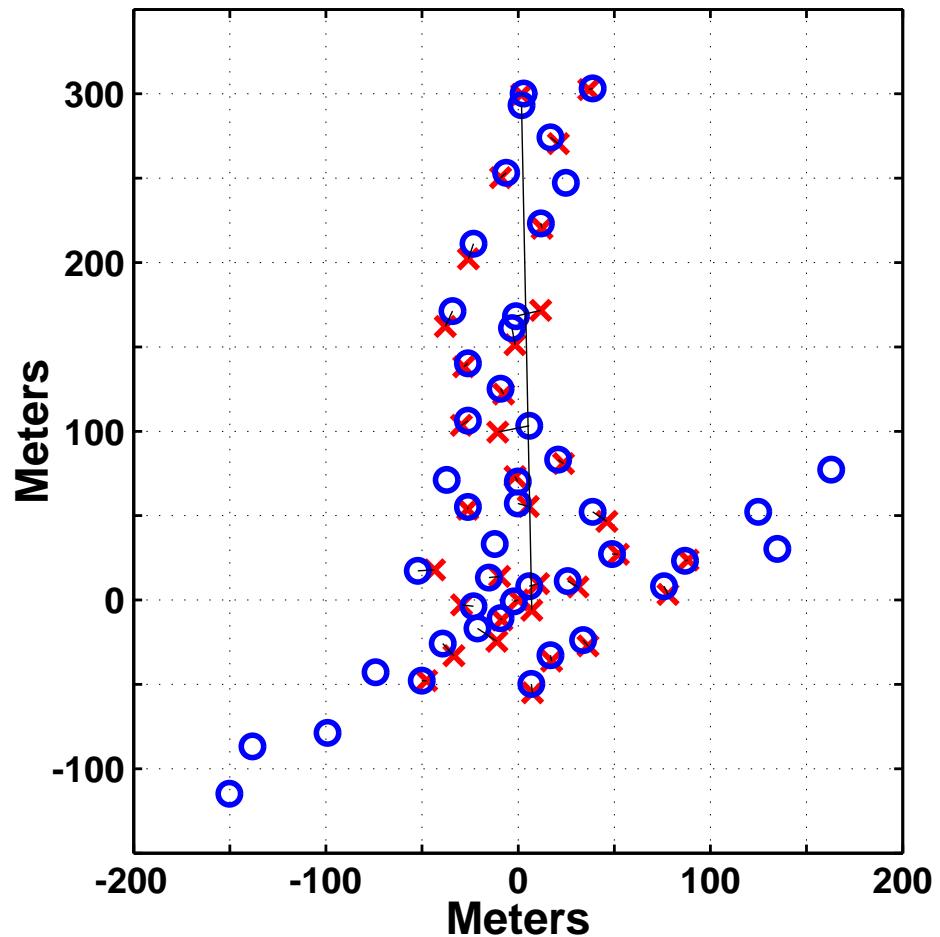
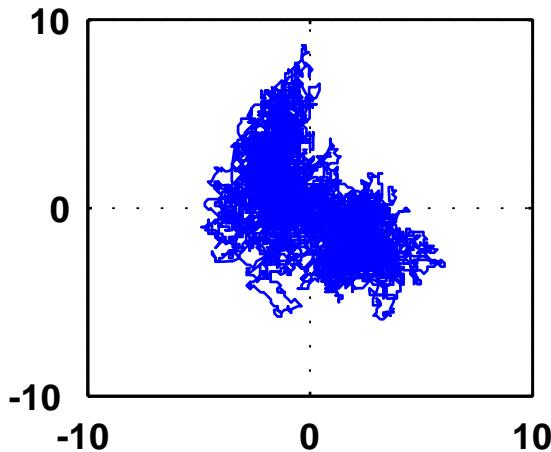
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# GPS averaging

- Handheld GPS used at SITEX02 for node surveying
- Single GPS measurement is accurate to 10m
- GPS averaging over several hours significantly improves the accuracy.





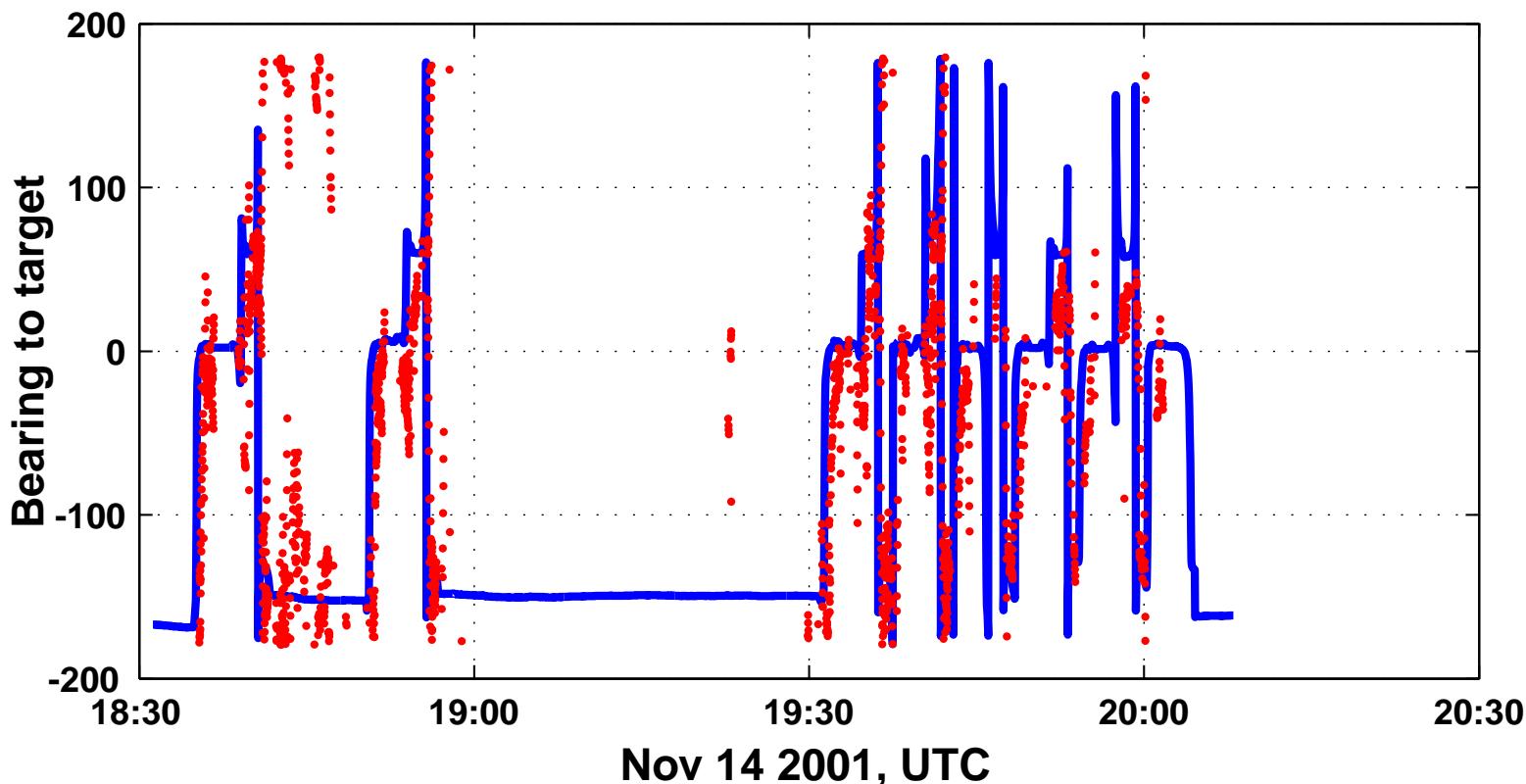
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# Reference coherent bearing estimates

- 5-element acoustic sensor
- Coherent bearing estimation & classification
- Provides additional ground truth for later analysis





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  - **Contributions**
  - **Future work**
  - **Publications**



# Contributions

- SITEX02: TDOA software ran in real-time over ISI Diffusion routing
- TDOA performance simulations- demonstrate benefits of cluster-based processing
- Enhanced SITEX02 recorded data by implementing time synch/GPS accuracy improvements
- Collected ground-truth bearing data
- Demonstrated bearing fusion and used Declarative Routing Protocol in Fort Benning Tanks Under Trees demonstration, Oct 2001.
- Released/documentated DRP software



# Future work

- **TDOA enhancements**
  - Improve frequency tracker for high-bandwidth data
  - Extend to multi-target tracking
  - Integrate with tracking/display system
- **Dynamic cluster formation**
- **Acoustic multipath mitigation**
- **On-line refinement of sensor locations and/or time synchronization**
- **NTP and Linux fixes to allow GPS time synchronization**



# Publications

- P. W. Boettcher and G. A. Shaw, “A Distributed Time-Difference of Arrival Algorithm for Acoustic Bearing Estimation”, in Proc. 2001 International Conf. on Information Fusion, vol. 1, Montreal, August 2001.
- P. W. Boettcher, J. A. Sherman, and G. A. Shaw, “Target localization using acoustic time-difference of arrival in distributed sensor networks”, to appear in SPIE AeroSense, Orlando, FL, April 2002.
- Project reports
  - Declarative Routing Protocol project report
  - TDOA simulation project report



# Bearing example

